Characteristics of high-speed water jet in water

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Abstract

This paper preliminarily describes the characteristics of high-speed water jets injected into water from an orifice. The main focus is to compare of the jet characteristics being the jets injected in ambient air and water. The high-speed liquid jets are generated by the impact of a projectile launched by a horizontal single-stage power gun designed and constructed at Department of Mechanical Engineering, Faculty of Engineering, Ubon Ratchathani University. The jets were visualized by a high-speed video camera and shadowgraph optical arrangement. From the shadowgraph images, the maximum averaged velocity of jet injected in air and water is estimated to be 1,282 m/s (Mach number or Ms = 3.77) and 374.24 m/s, respectively. Due to the supersonic motion of the jet injected in air, the oblique shock waves were created over its top part. The averaged velocity of jet injected in water is much slower than that in air because hydrodynamic drag is much higher than aerodynamic drag. That affects on the penetration distance of jet injected in water being shorter than that in air. The core jet, water vapor bubble, shock wave in water and rebound shock wave generated because of bubble collapse is obviously revealed.

Keywords: High-speed liquid jet, Horizontal single-state powder gun, Shock wave, Shadowgraph optical arrangement

1. Introduction

High-speed liquid jet has been studied for its wide applications such as cleaning and cutting technologies, mining and tunneling [1-4]. The high-speed liquid jet has also gained attention in combustion [5, 6] and medical applications [7, 8]. Recently, attention has begun to be focused on industrial applications of jet to underwater work [9] such as cutting marine structures and drilling at the bottom of the sea, since the energy density of high-speed jets is sufficiently high for such cutting and drilling. In 1996, Hitoshi Soyama [10] described phenomena occurring around ultrahigh-speed submerged water jet. Continue water jets were generated by a plunger pump, 70 MPa in maximum injection pressure, 22 l/min in flow rate. He visualized the water jet accompanied by very severe cavitations by shadowgraph technique and measured impulsive pressures around the jets by means of a pressure-sensitive film. He also clarified the effects of the injection pressure and the nozzle configuration on impulsive pressure of jet.

In 2009, K. Ohtani [11] reported the result of preliminary experiments of pulsed Ho:YAG laser-induced jets applied to drill a submerged rock specimen. He visualized the laser-induced water jets by a high-speed digital video camera with shadowgraphs technique. The jet speed was estimated to be about 40 m/s from shadowgraph images. He also measured high stagnation pressures generated by jet impingements. He found that simultaneously shock waves of about 22.7 MPa were generated at bubble collapse, which effectively cracked the surface of the rock specimens.

In previous studies, the submerged jet speed is quite low due to the limitation of jet generation technique as above mention. Hence, characteristics of high-speed jet submerged in water have not been clarified yet. To overcome the technical limitation of high-speed jet generation, the impact acceleration method or Bowden and Brunton method [12, 13] is applied to generate high-speed jets in this study. The formations of the jets injected in air and water are visualized by high-speed digital video camera with shadowgraph optical arrangement. Moreover, the difference of jet injected in air and water in jet penetration distance and velocity attenuation are analyzed. The vapor bubble mechanism of jet injected in water is also described in this paper.

2. Horizontal Single-Stage Powder Gun

Liquid jets are formed when pressurized liquids confined in a container are discharged through a nozzle hole and jet speeds are determined by the value of pressures. In general, the higher the pressures are, the higher the jet speed becomes. However, static pressures over GPa are hardly maintained in large volume metal vessels.

To produce high-speed jets, Bowden and Brunton [12, 13] enhanced pressures in a liquid filled a container by a momentum transfer created with a sudden impingement of a high-speed projectile as shown in Figure 1. Then shock waves are generated inside the container. The shock compression generates high pressures of a several GPa maintained for a few hundred microseconds, which is even more effective than adiabatic compression. Hence to obtain higher jet speeds, impact speeds should be as high as possible technically.

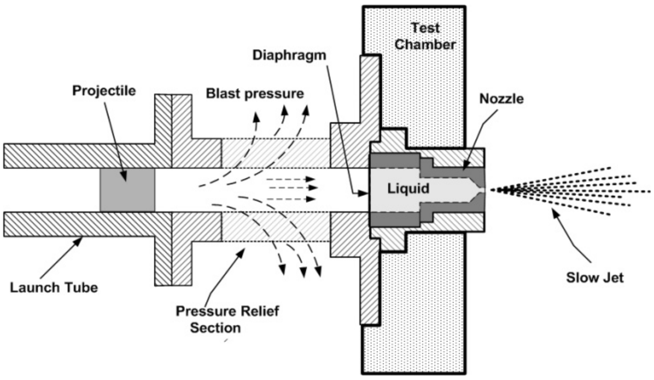

Fig. 1 The blast pressure or shock wave effect cause slow jet

The high velocity projection needed in this technique has been generated by the Horizontal Single Stage Powder Gun (HSSPG), shown in Figure 2. The HSSPG consists of launcher, launch tube, pressure relief section

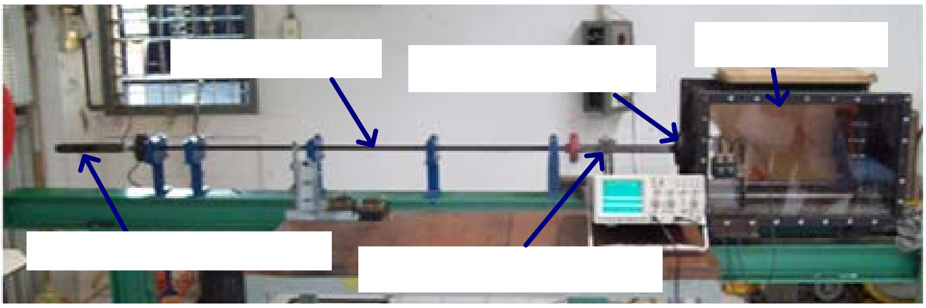

Fig. 2 Horizontal Single-Stage Powder Gun (HSSPG)

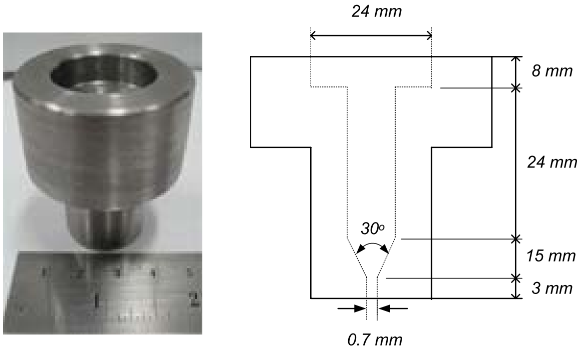

Fig. 3 Nozzle geometry

and test chamber. The launch tube has a diameter of 15 mm and length of 1.5 m. The pressure relief section has a length of 38.5 cm, which is designed to diminish the blast wave in front of the projectile. The pressure relief section has 4 slots, each slot has 4 mm in width and 345 mm in long. The test chamber is a square tank of 350 X 350 mm in width and 590 mm in long, with two polymethyl methacrylate (PMMA) windows on two sides for visualization. The projectile is made of Polymethyl Methacrylate (PMMA), is cylindrical shape with diameter of 15 mm and length of 8 mm (weight of 0.92 g). The HSSPG has been employed to generate the high-speed liquid jet velocity of 550 to 2,290 m/s in each gunpowder weights. The nozzle that is connected to pressure relief section is made of mid-steel, and its dimension is shown in Figure 3. Gunpowder of 5 g is used for generating the jets in this experiment.

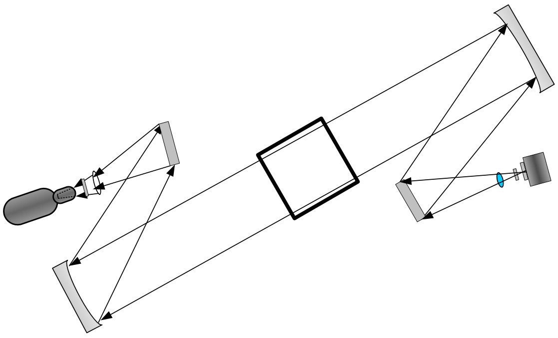

Fig. 4 Shadowgraph optical setup for high-speed digital video recording

3. Visualization method

In this study, we used a high-speed video camera and shadowgraph optical arrangement for visualization as shown in Figure 4. The dynamic jet formation is quantitatively measured by sequential observations. A Xenon lamp is used as a light source. The source light is collimated passing through a concave lens and a circular slit. The laboratory space is limited that we combined two plane mirrors of diameter 190 mm. Two paraboloidal schlieren mirrors of diameter 300 mm were used for collimating source light beam passing the test section area. A Nikon 60 mm Macro lens was

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used to focus the object image on the high-speed video camera screen. The high-speed video camera is a Photron SA5 at frame rate of up to 30,000 f/s, maximum shutter speed of up to 1 μs, and 5.46 seconds record time at full resolution.

4. Jet formation

Using a high-speed video camera, Photron SA5 could record shadowgraph images at frame rate of up to 30,000 f/s and shutter speed of of 1 μs. Such a sequential recording is very useful to observe the jet formation.

In Figure 5, only selective 6 images are presented. Jet formations of water were discharged into atmospheric air. The water jet shows the slim width and looks more elongated to be over 213 mm at 166 μs. Its averaged speed at 166 μs is 1,282 m/s and Ms = 3.77 in room temperature air. The jet motion is supersonic so that oblique shock waves are created over its top part and also the jet's nodes. At the earlier stage, the inclination angle of the first oblique shock wave is about 15^{o} which corresponds to the oblique shock Mach number of 3.86.

The jet speed estimated from the shock inclination angle differs from that obtained from the video images. This is attributable to the fact that the relationship between the oblique shock angle and a supersonic body is valid to a supersonic solid body but in this case the jet boundary consists of distributed liquid droplets/air mixture and irregularly shaped water surface. The sound speed defined around such a jet boundary is no longer the same as that of air and slightly smaller than that in air.

In addition to this fact, the liquid jet's frontal stagnation area has a dispersed structure and a kind of ablation takes place. Not only fragmentation from bulk liquid to droplets but also vaporization on the liquid surface simultaneously takes place. As a result of it, the corresponding inclination angle of shock wave and the shock stand-off distance over the liquid jet not necessarily coincides with those over a solid body moving at the identical supersonic speed. The discrepancy also exists between the estimated jet speed from shock inclination angle and that from the video images.